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# A new approach to sum frequency generation of single-frequency blue light in a coupled ring cavity

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## ABSTRACT

We present a generic approach for the generation of tunable single-frequency light and demonstrate generation of more than 300 mW tunable light around 460 nm. One tapered diode laser is operated in a coupled ring cavity containing the nonlinear crystal and another tapered diode laser is sent through the nonlinear crystal in a single pass. A high conversion efficiency of more than 25 % of the single-pass laser is enabled by the high circulating power in the coupled cavity. The system is entirely self-stabilized with no need for electronic locking.

**Keywords:** tapered diode laser, coupled cavity, sum frequency generation, optical feedback

## 1. INTRODUCTION

Many applications within biophotonics and spectroscopy rely on visible laser sources with the possibility of selecting the desired wavelength. Such lasers can be challenging to develop with the exact requirements for the applications. Diode lasers in the visible spectral region are available in the red, green and blue. The output power from single-mode visible diode lasers is limited to about 100 mW and these lasers tend to operate in multiple longitudinal modes. Higher output power is possible using broad area diode lasers but at the expense of a decrease in spatial beam properties. Single-frequency output from visible diode lasers can be obtained from external cavity diode lasers or from diode laser with internal gratings. Up to 100 mW was recently demonstrated in the red spectral region at 635 nm using a DBR grating for frequency selection<sup>1</sup>. Using internal gratings, however, inherently limits the tunability. Visible external cavity single-mode diode lasers typically emit lower output power.

Frequency doubling is a well-established method for generation of visible light by frequency conversion of near-infrared lasers. A lack of suitable gain media at various wavelengths limits the spectral coverage of second harmonic generation (SHG). Another very flexible source of tunable visible light is an optical parametric oscillator, but these have the disadvantage of being complicated to operate and require high pump power sources with excellent beam quality. Sum-frequency generation (SFG) has the possibility to generate light throughout most of the visible spectrum by proper choice of the fundamental laser wavelengths. A well-known application is for generation of light at the Sodium D2 resonance at 589 nm. By mixing two diode pumped solid state lasers, tens and hundreds of mW can be generated in a single pass through a nonlinear crystal<sup>2,3</sup>. SFG between a diode laser and a solid state laser was shown to generate light at 492 nm<sup>4</sup> and recently generation of up to 4 W of green light at 531 nm was demonstrated by SFG between two beam combined DBR tapered diode lasers<sup>5</sup>. Although single-pass SFG is a simple and robust method for generation of visible light, the conversion efficiency is limited by the input power available from the interacting lasers. Higher conversion efficiency can be obtained by resonating one or both interacting beams in a high-finesse resonator. This can be achieved by placing the nonlinear crystal inside the cavity of a laser<sup>6-10</sup> or in an external enhancement cavity<sup>11</sup>. 41 % conversion efficiency of the single-pass laser has been demonstrated in this way efficiently generating yellow light<sup>7</sup> and the possibility of generating almost any desired wavelength was demonstrated by Karamehmedovic et al. generating light at 488 nm by mixing a solid state laser and a tunable diode laser<sup>9</sup>. Higher conversion efficiency can be obtained by resonating both interacting waves inside a laser cavity<sup>12</sup> or external cavity<sup>13</sup>, however at the expense of increased complexity and instability.

Recently coupled cavity operation of tapered amplifiers and SHG has been demonstrated to generate high output power and excellent beam quality in the blue and green spectral ranges<sup>14,15</sup>. Skoczowsky et al. showed operation of a 976 nm tapered amplifier operated in a unidirectional ring cavity coupled to a compact ring cavity with the SHG material enclosed<sup>14</sup>. More than 300 mW of diffraction limited single-frequency output at 488 nm was obtained. In a similar approach, more than 500 mW of tunable green light was demonstrated<sup>15</sup>. The coupled cavity setups have the advantage of being entirely passively locked by optical feedback to the tapered amplifiers.

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Here, we present a generic approach for efficient generation of single-frequency visible light by SFG between two tapered lasers<sup>16</sup>. One external cavity tapered laser is single-passed through a nonlinear crystal contained in a coupled ring cavity containing the second tapered amplifier. In the coupled cavity, the power of one tapered laser is enhanced to increase the single-pass conversion efficiency to more than 25% resulting in generation of more than 300 mW of single-frequency light at 459 nm. The resulting beam is diffraction limited due to nonlinear beam lean-up of the single-pass laser inside the nonlinear crystal. The laser system relies on optical feedback and no electronic locking is required. This approach can be expanded to cover the entire visible spectrum by proper choice of tapered amplifiers.

## 2. EXPERIMENTAL SETUP

The experiment was constructed from two different laser parts. One part was a coupled ring cavity tapered laser including the nonlinear frequency conversion crystal and the other part was an external cavity tapered laser which was single-passed through the nonlinear crystal to efficiently generate light at the sum frequency. A sketch of the experimental setup can be found in figure 1.

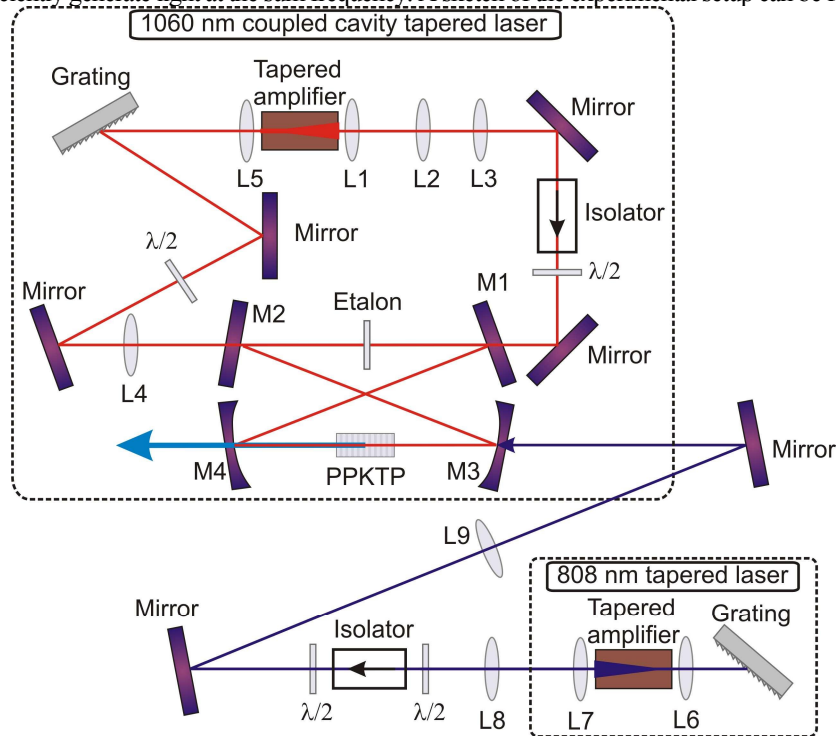


Figure 1. Experimental setup of SFG between the coupled cavity tapered laser and the external cavity tapered laser.

The main component of the coupled cavity tapered laser was the tapered amplifier. In the experiments, a 4 mm long tapered amplifier consisting of a 1 mm long ridge waveguide section and a 3 mm tapered section was used. The tapered section had an angle of  $4^\circ$  giving an aperture width of  $210\ \mu\text{m}$ . The active region of the amplifier was constructed as a super large optical cavity<sup>17</sup> resulting in a vertical far field angle of about  $22^\circ$  (FWHM). The amplifier facets were passivated and coated to a rear facet reflectivity below 0.1% and a front facet reflectivity of about 2%. The amplifier was first characterized in a Littrow external cavity setup<sup>18</sup>. At 3 A driving current, the laser was tunable in the 1049 nm – 1093 nm wavelength range with a maximum output power of 1.79 W obtained at 1064 nm. The power was higher than 1.6 W in the 1052 nm to 1080 nm wavelength range. The output beam along the slow axis had a strong central lobe enclosing about 80% of the output power and some low-intensity higher order modes. This resulted in a beam propagation factor of  $M^2 = 1.3$  and 2.8 in the fast and slow axis direction, respectively.

In the coupled ring cavity, the output from the tapered amplifier was collimated in the fast axis using an aspherical lens with a focal length of 3.1 mm (L1). A cylindrical lens with a focal length of 30 mm (L2) was used to correct for the astigmatism of the tapered amplifier and collimate the beam in the slow axis direction. A spherical lens (L3) with 250 mm focal length focused the beam into the enhancement cavity consisting of mirrors M1, M2, M3 and M4. A 30 dB optical isolator ensured unidirectional operation of the ring laser and a half-wave plate rotated the polarisation to

horizontal as needed for efficient SFG in the nonlinear crystal. The four mirrors in the bow-tie enhancement cavity were coated as follows: M1 (plane) was coated for 95% reflectivity at 1064 nm, M2 (plane) was coated for 98% reflectivity at 1064 nm, M3 (R = 50 mm) was coated for high reflectivity at 1064 nm and highly transmitting at 808 nm and M4 (R = 50 mm) was highly reflecting at 1064 nm and highly transmitting at 532 nm. M4 had a residual reflectivity at 459 nm of about 10%. The cavity was constructed to support a beam waist diameter of 60 x 70  $\mu\text{m}$  between the curved mirrors. A 10 mm long periodically poled KTP (PPKTP) crystal was positioned in this beam waist. The AR-coated PPKTP crystal was poled with a period of 5.6  $\mu\text{m}$  for SFG between 1064 nm and 808 nm. A 125  $\mu\text{m}$  thick uncoated YAG etalon was included in the cavity to improve stability. The light exiting M2 was collimated using a 100 mm focal length lens (L4) and incident on a 1200 grooves/mm grating for wavelength selection before coupled into the tapered amplifier through a 3.1 mm focal length lens (L5). A half-wave plate was included in order to optimize the power coupled to the tapered amplifier.

Operation of the tapered amplifier in this external cavity resulted in the same tuning range as in the Littrow setup. The output beam profile was purely TEM00 with a beam propagation factor of 1.03, a result of the mode-cleaning properties of the cavity.

The 808 nm external cavity tapered laser was operated in the Littrow geometry with a 1200 grooves/mm diffraction grating for wavelength selection<sup>18</sup>. The output was collimated in the fast axis using a 3.1 mm focal length aspherical lens (L7) and a 40 mm focal length cylindrical lens (L8). An optical isolator with >30 dB isolation was inserted to prevent feedback to the tapered laser and two half-wave plates were used to control the power and polarization of the light incident on the PPKTP crystal. The light from the external cavity tapered laser was tunable in the range 792 nm – 819 nm (FWHM) with an output power of up to 1.28 W after the optical isolator. The beam propagation factor was measured to  $M^2 = 1.3 \times 1.9$  in the fast and slow axis respectively.

### 3. EXPERIMENTAL RESULTS

The circulating power in the enhancement cavity could be monitored by measuring the power leaking the cavity through mirrors M3 and M4. In this way it was found that the circulating power in the enhancement cavity can reach approximately 15 W when no light at 808 nm was incident on the PPKTP crystal.

The wavelength of the external cavity tapered laser was tuned to 807.5 nm and the coupled cavity tapered laser was tuned to 1063.5 nm. These wavelengths allowed for phase matching of SFG in the PPKTP crystal at a temperature of 34°C.

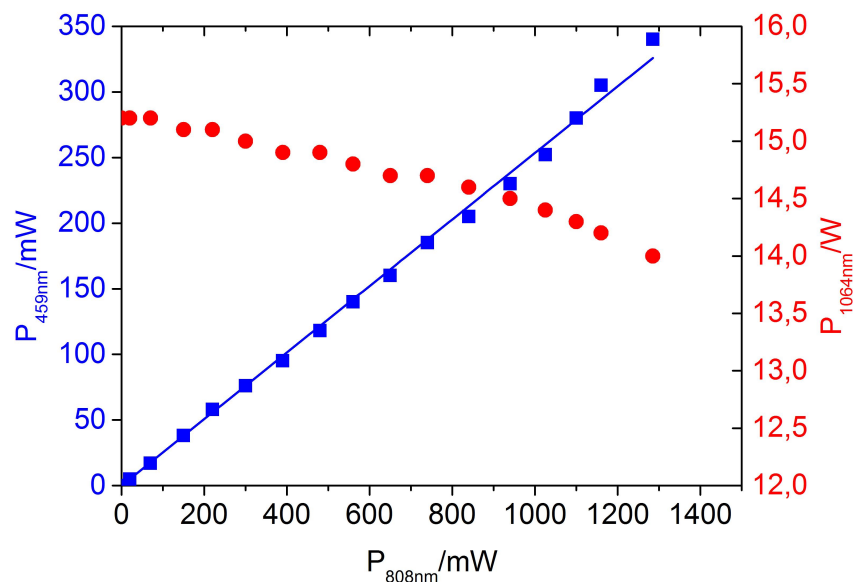


Figure 2. Measured output power at 459 nm (blue squares) and circulating power at 1064 nm (red dots) with varying input power at 807.5 nm.

At maximum input power of 1.28 W from the 807.5 nm tapered laser, an output power of 340 mW at 459 nm was measured with 14 W circulating power in the enhancement cavity. The power characteristics are shown in figure 2. It can be seen that the generated output power at 459 nm increases approximately linearly with the input power at 807.5 nm. It is further seen that the circulating power at 1063.5 nm decreased when the losses due to the SFG process increased. The losses induced by the SFG process increases linearly with the incident power as opposed to SHG where the losses increase quadratically. The extracted power of 340 mW was obtained without taking the losses of the nonoptimized components into account. The mirror M4 and the dichroic mirror were not optimized for 459 nm and when these losses are taken into account, more than 400 mW of generated light can be deduced. This corresponds to a single-pass conversion efficiency of more than 31% and a nonlinear conversion efficiency of 2.2%/W in the PPKTP crystal.

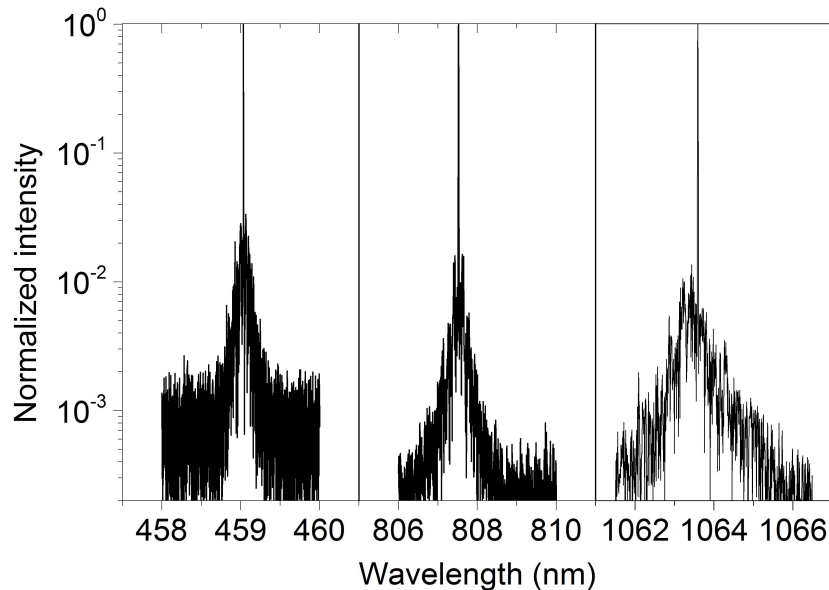


Figure 3. Measured spectra at 459 nm, 807.5 nm and 1063.5 nm.

The spectrum of the light generated by SFG was determined by the spectral properties of the 807.5 nm laser and the 1063.5 nm laser. As both of these lasers are single-frequency, it is expected that the blue light is also single frequency. This was verified using an optical spectrum analyser and the linewidth measured at 459 nm was 2 pm limited by the resolution of the optical spectrum analyser as shown in figure 3. To verify single-frequency operation of the two mixing lasers, scanning Fabry Perot interferometer (FPI) measurements were performed on the light at the two wavelengths. The FPI measurements are shown in figure 4, with a measured linewidth of below 12 MHz at 807.5 nm and 10 MHz at 1063.5 nm, respectively. These linewidths were limited by the resolution of the FPIs. Mirrors for an FPI at 459 nm were not available but single-frequency operation at this wavelength can be deduced from the FPI measurements on the other wavelengths.

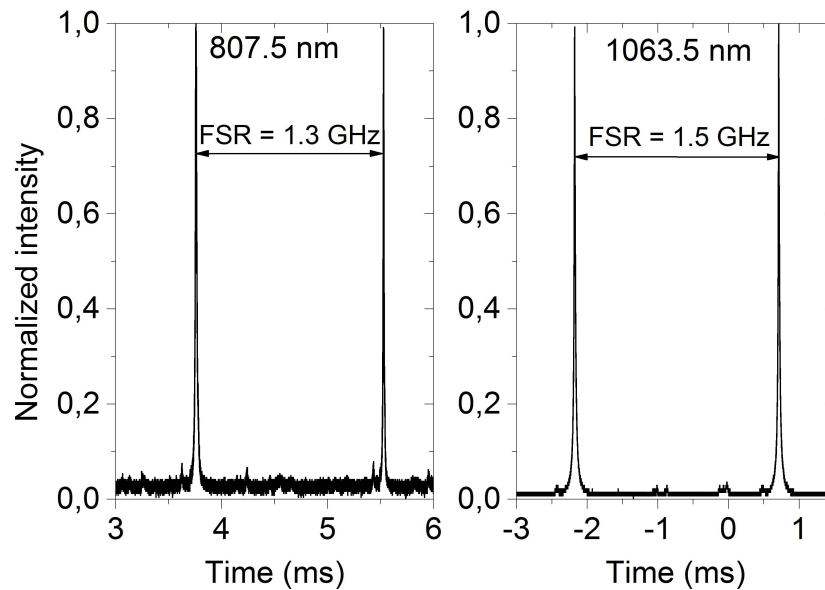


Figure 4. Scanning Fabry Perot measurements on light at 807.5 nm and 1063.5 nm.

By selecting the tapered amplifiers to fit the desired generated wavelength, it is possible to generate light throughout the visible spectrum and also cover parts of the UV spectrum. Tuning of the generated light was demonstrated by tuning the 808 nm external cavity tapered laser. In this way, blue light in the 458.5 nm – 460 nm range was generated. By fully exploiting the tunability of the two tapered amplifiers and using a different nonlinear crystal, a tuning range of 451 nm – 468 nm would be possible.

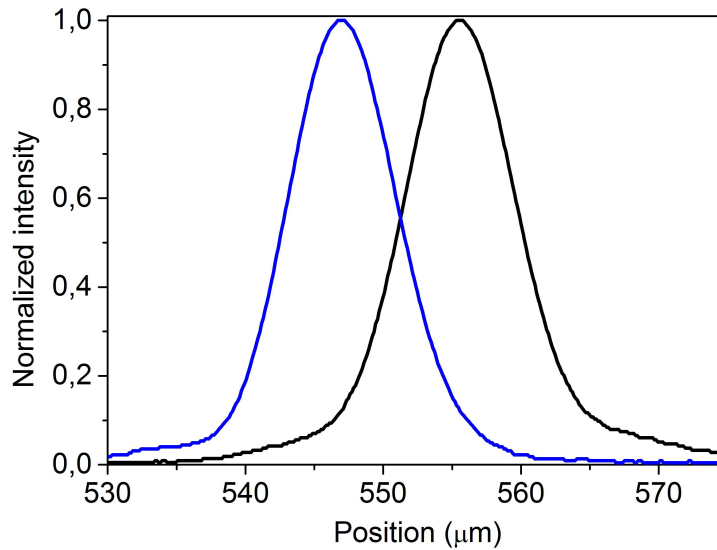


Figure 5. Beam profiles in the vertical and horizontal direction of the 459 nm light.

The spatial properties of the generated blue light are determined by a combination of the spatial properties of the two different mixing beams and by the overlap between the beams. Karamehmedović *et al.* showed that it is possible to use the SFG process between a Gaussian beam and a non-Gaussian beam to clean up the spatial properties by a proper selection of the overlap between the two beams<sup>19</sup>. Here, we used the Gaussian beam in the enhancement cavity to clean up the near diffraction limited beam from the external

cavity tapered laser. The result was a generated blue beam that was nearly Gaussian and close to diffraction limited with a beam propagation factor  $M^2 < 1.15$  in both directions as shown in figure 5 and figure 6.

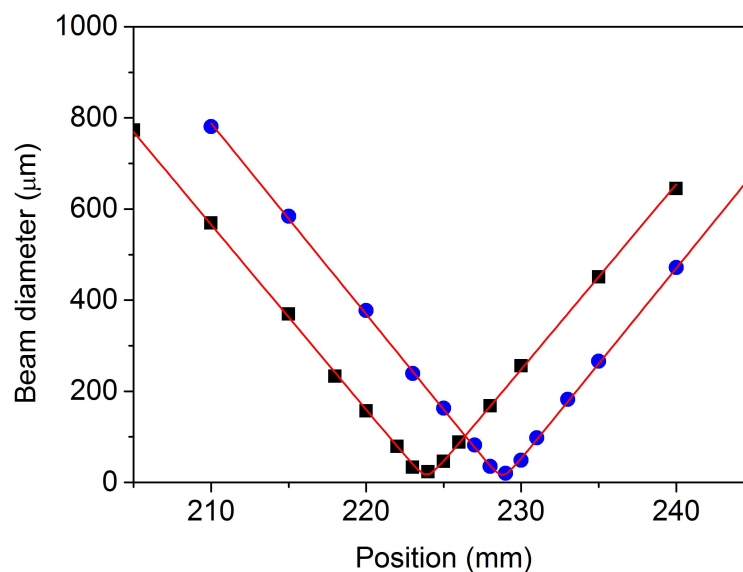


Figure 6. Measured beam widths for the 459 nm light.

## CONCLUSION

A generic approach for generation of single-frequency tunable visible light has been demonstrated. An external cavity tapered laser was single-passed through a nonlinear crystal enclosed in a coupled ring cavity tapered laser. Efficient sum frequency generation was achieved in the nonlinear crystal as a result of the increased circulating power in the ring cavity. We applied this approach to two tapered amplifiers at 808 nm and 1064 nm to generate more than 300 mW of nearly diffraction limited blue light at 459 nm. We demonstrated wavelength tuning of 1.5 nm and a significantly wider tuning range is possible by selecting a different nonlinear crystal. Other spectral regions can easily be reached by proper selection of tapered amplifiers.

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